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THE MET AND THE CLO
Part 1. Restatement of the Original Definitions

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FOREWORD

The science of clothing, which is still in a formative state, embraces the study not only of protective materials but also of environment. It involves concepts originating in part from physiology and in part from climatic engineering. The Committee on the Biophysics of Clothing, sponsored by the U. S. Army Natick Laboratories, has guided many investigations pertinent to the subject of this paper, namely the flow of heat and moisture through clothing -- the standard units of measurement of which are the met and the clo. These units are the creation of three environmental physiologists, A. P. Gagge, A. C. Burton, and H. C. Bazett.

The purpose of Part I of this paper is to help make the concepts of the met and the clo more widely useful by converting the original units to commonly used engineering terms. It provides an equation for expressing the number of clo in terms of climatic temperature. Toward this end, further contributions of A. P. Gagge, now of the John B. Pierce Foundation Laboratory, New Haven, Conn., have proved invaluable.

Part II will extend the concept of the clo to embrace conditions of varying humidity.

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ABSTRACT

The definitions of the met (50 Kcal/m^2 hr = 18.5 Btu/ft^2 hr) and the clo (5.55 Kcal/m^2 hr °C = 1.14 Btu/ft^2 hr °F), as derived from the original paper (1941) by the three physiologists Gagge, Burton, and Bazett, are discussed in terms familiar to heat transfer engineers. The number of the clo required, n, is stated as a function of the temperature, t (in °F), by the equation: $n = 0.0814 (92-t) - 0.792$. This gives a value of n of 1.0 at t = 70°F.

THE MET AND THE CLO

1. Introduction

The unit called the met is used for expressing the metabolic heat production of the human body. One met is the heat production under rest conditions. A met is defined as 18.5 Btu/ft^2 hr (50 Kcal/m^2 hr). This is equivalent to the per-man value of 400 Btu/hr that is familiar to engineers and is based on a surface area of 2.0 m^2 as initially defined by DuBois.*

The unit called the clo is used for measuring the insulation value of clothing. By definition, one clo is required by an individual at rest for comfort at normal room temperature. In heat transfer terms, one clo is identical with a clothing conductance value of 1.14 Btu/ft^2 hr °F (5.55 Kcal/m^2 hr °C).

These units were devised by three physiologists who provided not only a practical system of measurement, as chiefly intended, but also a basic approach to defining comfort in physical terms. It is unfortunate that the met and the clo have fallen somewhat into disuse. This is due in part to the form of the original equations.

This paper attempts to convert the terms met and clo into those common to engineers. It purports further to take a new look at the significance of the concepts supporting these units and believed to have an important bearing on current problems.**

2. Interpretation of Original Definition

Three concepts used by Gagge and his associates for purposes of analysis are of particular interest: 1) the definition of comfort as a steady state equilibrium between an environment and an area of skin at some agreed mean temperature, such as 92°F; 2) the notion that an adequate conceptual model need be nothing more than any square foot of surface; and 3) the designation of the normally clothed inactive subject, under free convection at normal room temperature, as a standard of reference for general calculations. These are especially useful conceptual devices for computing the ventilation required for an individual isolated as, for example, in a space suit.

Table I summarizes the data provided by Gagge and his associates and presents other data which have been derived therefrom. The figures given have proved to be useful for purposes of calculation and as the specifications of a normal state. It is notable, however, that the

*DuBois, E. F. The Mechanism of Heat Loss and Temperature Regulation. Stanford Univ. Press, Stanford, Calif., 1937.

**Gagge, A. P., A. C. Burton, and H. F. Bazett. A Practical System of Units for the Description of Heat Exchange of Man with his Environment. Science, 94, 428 (Nov. 7, 1941).

TABLE I

Reference Conditions for the Definition of the Clo

Specified in the original definition

$$I_{cl} = (t_s - t)/q_s - I_A = (33 - t\ ^\circ C)/38 - .14 = .18\ ^\circ C/(Kcal/m^2 hr)$$
$$= .88\ ^\circ F/(Btu/ft^2 hr)$$

Activity level, met	1
Skin temperature, t_s (°F)	92
Room temperature, t	70
Room humidity, W (50% R. H.)	0.008
Air velocity, max V (ft/min)	20
Evaporative heat loss (E/A), q_L (Btu/ft^2 hr)	4.5
Other heat loss (R+C)/A), q_s (Btu/ft^2 hr)	14.0
Insulation of clothing, I_{cl} °F(Btu/ft^2 hr)	0.88

Implicit in original definition (see text)

$$n = [(t_s - t)/q_s - 1/(h_r + h_c)]I_{cl} = [(33-t)/38 - .14]/.18 \quad (^\circ C)$$

Conductance of one-clo layer, C_c(Btu/ft^2 hr °F)	1.14
Surface coefficient of heat transfer, $h_r + h_c$	1.44
Insurface temperature, clothing, t_c	92
Outsurface " " , t_{cl}	79.7
Clo value at 1 met, 70°F	1
Heat transmittance, U_1(Btu/ft^2 hr °F)	0.636

Symbols

U	$= 1/(n/C_c + 1/(h_r + h_c))$
C_c	$= 1/.876 = 1.14$
t_{cl}	$C_c(92 - t_{cl}) = 14.0$ or $t_{cl} = 79.7\ ^\circ F$
U_1	$U_1\ (92 - 70) = 14.0$ or $U_1 = 0.636$
$h_r + h_c$	$U_1 = 1/(1/1.14 + 1/h_r + h_c)) = 0.636$ or $h_r + h_c = 1.44$
Eq. (c)	$U \Delta t = q_s$ or $n = .0814\ (92 - t) - 0.792$

definition of the clo is not simple. Were this definition to be considered by a standardizing agency, it could entail no little controversy and negotiation. However, what the original authors said is, per se, necessary and sufficient.

The essentials of the original statement may be quoted as follows:

> The proposed thermal activity unit may be defined as 50 Calories per hour per square meter at the surface of the individual (or 18.5 Btu/hr/sq ft). This is approximately the metabolism of a subject resting in a sitting position under conditions of thermal comfort. This unit may be called the <u>met</u> . . . . .
>
> The unit for thermal insulation of clothing is logically the amount of insulation necessary to maintain in comfort such a sitting-resting subject in a normally ventilated room (an air movement of 20 ft/min or 10 cm/sec) at a temperature of 70°F (or 21°C) and a humidity of the air which is less than 50 percent. This unit of insulation is called the <u>clo</u> . . . . .
>
> There is evidence that, in the last analysis, comfort is dependent largely on skin temperature. The optimal average skin temperature appears to be 92°F (33°C) . . . . .
>
> For men in the conditions already specified, it may be assumed that 24% of the resting metabolic heat is dissipated by evaporation of insensible perspiration. The remaining heat transmitted through the clothing is therefore 38 (76% of 50) Calories/hr/sq m. The difference in temperature concerned is 33 - 21°C. . . . .
>
> The total insulation, which is the sum of the insulation of the clothing, I_{cl}, and that of the ambient air, I_A, is given in metric units by the equation (33-21/38 = .32).

$$I_{cl} + I_A = 0.32 \quad \frac{°C}{Kcal/hr/sq\ m} \qquad (a)$$

It is notable that the temperature difference considered in Equation (a) is that between the skin and the ambient air. The authors go on to state that I_A (thermal resistance of the clothing -air interface) is known to have a value of 0.14 in the units cited ($h = 1/I_A = h_c + h_r = 1/0.14 = 7.0$ Kcal/m^2 hr °C. The insulating value of the clothing alone is then 0.32 - 0.14 = 0.18, or

$$I_{cl} = 0.18\ ^{o}C/Kcal/hr/m^2) = 0.876\ ^{o}F(Btu/hr/ft^2) \qquad (b)$$

where the temperature difference is that between the skin and the surface of the clothing. The assumption is implicitly made that there is no resistance to heat flow at the surface of the skin, on the inner clothing surface, or across the gap between these surfaces. The value of 0.876 thus refers to the resistance of the clothing alone, as between the temperatures of the two surfaces. The reciprocal value of 1.14 is the conductance, C_c. From this, it follows that the number of clo necessary to maintain the original equilibrium is:

$$n = [(92 - t)q_s - 1/1.44]\ 1.14 \qquad (c)$$

$$= .0814\ (92 - t) - .792$$

This is spelled out in Table II for various temperatures.

TABLE II

Number of Clo Required for Comfort Equilibrium at Various Temperatures (1 met)

Temperature (t) (°F)	Number of clo (n)
70	1.0
60	1.81
57.8	2.0
50	2.63
45.4	3.0
40	3.44
33.3	4.0
30	4.25
20	5.07
0	6.70
-20	8.33

Example: The number of clo required at 30°F is

$$.0814\ (92 - 30) - .792 = 4.25$$

3. <u>Discussion</u>

The foregoing statement, including the three equations as well as Tables I and II, is consistent with the original definitions of the met and the clo. These units are of great usefulness in a field of technology still in the process of formulation.

It is readily possible to read further implications into the original statement, some of which need to be examined in the light of present practice. In the area of protective garments, the question arises - is it enough to consider only sensible heat in relation to the comfort of clothing - what about the effect of the latent heat?

The clo takes no account of humidity. This comes about from the assumptions, implicit in the original defintion, that 1) the clothing offers negligible resistance to the flow of moisture; 2) all sweat is to be found on the skin surface as a liquid; and 3) all temperatures within the clothing are above the local dew point. The outcome of such considerations is discussed more fully in Part II of this report.

The clo unit has been used only for temperatures below the 70°F level. If, however, we extend Equation (c) to higher temperatures, we get such values as these:

t	n
82.3	0
80.0	.18
75.0	.58

That is, above 70°F, values of n are less than one. Above 82.3°F, negative values appear. According to definition, then, a nude man whose weighted skin temperature is 92°F is in equilibrium in a room at 82.3°F. In this situation, only the factor originally identified as I_A is involved, represented here by the reciprocal of the sum of the two surface coefficients h_r and h_c.

These considerations may be carried further by noting that h_r, the unit area radiation emittance of the human skin, is commonly approximated as .99, making the value of h_c .45. This is a matter capable of examination by means of dimensionless equations, such as are used to describe heat transfer from cylindrical or flat surfaces, consistent with the given velocity and air properties. In turn, h_c may be used to derive a consistent value of h_D, the coefficient of mass transfer, as explained in Part II of this report.

4. Summary

The met and the clo are useful units likely to find wide application in the fields of comfort physiology, protective clothing, and textile engineering. The 1941 definitions of Gagge, Burton, and Bazzet are sound and consistent. The original set of specifications, into which may be read further data, provide a useful norm for a variety of calculations involving air conditioning. The conceptual devices of the original authors also have wide application. A convenient equation for the calculation of the required number of clo at 1 met, for any ambient temperatures below 82.3°F is:

$$n = .0814\ (92 - t) - .792$$

5. Acknowledgment

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APPENDIX

List of Symbols and Numerics

n	number of clo	
m	metabolic heat per unit area	Btu/ft^2hr
E	heat loss by evaporation	Btu/hr
R	heat loss by radiation	Btu/hr
C	heat loss by convection	Btu/hr
q_s	sensible heat loss per unit area	Btu/ft^2hr
q_L	latent heat loss per unit area	Btu/ft^2hr
C_c	conductance of clothing ($1/I_{cl}$)	$Btu/ft^2hr\ ^\circ F$
U	overall coefficient of heat transfer (transmittance)	$Btu/ft^2hr\ ^\circ F$
t	room temperature	$^\circ F$
t_{cl}	temperature of outside surface of clothing	$^\circ F$
t_s	skin temperature	$^\circ F$
Δt	$t_s - t$	$^\circ F$
h_c	coefficient of convective heat transfer	$Btu/ft^2hr\ ^\circ F$
h_r	coefficient of radiative heat transfer	$Btu/ft^2hr\ ^\circ F$
I	see Table I	
W	absolute humidity	lb/lb

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